An initial assessment of the VIIRS onboard calibration using DCC and desert referenced to the Aqua-MODIS calibration

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ABSTRACT

The CERES observed EBAF 12-year TOA flux dataset are used to monitor the Earth's climate and in validating climate models. The associated cloud properties are retrieved from a fusion of MODIS and geostationary imagers. The quality of these cloud properties relies on the absolute calibration of these imagers. The geostationary imager radiances are calibrated against the Aqua-MODIS calibration reference in order to retrieve uniform cloud properties both spatially and temporally. Any calibration discontinuity or artifact may be interpreted as a climate trend. CERES record will be extended using CERES fluxes onboard NPP. CERES will need to tie the VIIRS with the Aqua-MODIS calibration in order to provide a seamless record of cloud and flux properties.

This paper will present initial assessment results for interconsistency between VIIRS and Aqua-MODIS calibration of matching visible channels. Empirically derived exoatmospheric VIIRS radiance models for deep convective clouds and deserts invariant targets are used to assess the initial onboard calibration of VIIRS. The VIIRS models are based on characterizing these invariant targets with Aqua-MODIS as an absolute calibration reference in order to tie the VIIRS calibration to Aqua-MODIS. Correction for spectral band differences in the VIIRS and MODIS channels is performed using the SCIAMACHY hyperspectral data.

Keywords: CERES, VIIRS, MODIS, radiometric calibration, SCIAMACHY, invariant targets

1. INTRODUCTION

The Clouds and the Earth's Radiant Energy System (CERES) project provides the science research community with climate quality TOA and surface fluxes and the associated MODIS cloud and aerosol properties, in order to monitor the Earth's climate and for the validation of climate models. One important aspect of successful of a climate monitoring mission is post-launch calibration and characterization of satellite instruments. The CERES instantaneous broadband calibration radiance stability is 0.2% per year[1], and is maintained through a quality on-board calibration system. CERES also incorporates 3-hourly geostationary (GEO) fluxes and cloud products to derive broadband fluxes and cloud properties that fill the gap between CERES observed fluxes and MODIS clouds onboard the sun-synchronous Terra (10:30 AM) and Aqua (1:30 PM) orbits. The fusion of the CERES and GEO radiances in one product is possible only if both the measurements are consistently calibrated on an absolute radiometric scale.

Due to lack of on-board calibration the GEO visible channels are calibrated vicariously prior to their use in the CERES data products. Currently CERES inter-calibrates the GEO visible radiances against Aqua-MODIS Band 1 (0.65 μm) by ray-matching co-incident, co-angled, and co-located regions imaged by both the sensors over an equatorial domain centered at the GEO sub-satellite point[2]. MODIS is widely regarded as a well-calibrated multi-band instrument. This ensures consistent cloud properties between MODIS and GEOs as well as stable GEO derived broadband fluxes across GEO satellite domains in both space and time. The GEO calibration stability is further validated through the use of multiple invariant targets including deserts and deep convective clouds (DCC), which are also referenced to the MODIS calibration[3].

The CERES Flight Model-5 (FM-5) instrument on the Suomi NPP spacecraft, which was launched on October 28, 2013, will continue the broadband flux data record begun by the CERES instruments on-board Terra and Aqua spacecrafts. Similarly, the Visible Infrared Imaging Radiometer Suite (VIIRS), will continue the Terra or Aqua_MODIS imager cloud and aerosol retrievals. During the overlap period between Aqua and NPP imager records, will therefore require that the VIIRS and MODIS visible radiances are placed on the same radiometric scale in order to provide a seamless record of cloud and flux properties.

This paper concentrates on an initial assessment of the VIIRS M5 (0.65 μm) calibration using invariant desert and DCC targets that are referenced to the Aqua-MODIS Band 1 (0.65 μm) calibration. Only certain scan angle positions are compared, since observations over the desert are limited to near-nadir (viewing zenith < 10°), whereas for DCC viewing zenith angles up to 40° are permitted. The VIIRS M5 channel is spectrally different than the Aqua-MODIS Band 1. During inter-comparison, the SRF difference between the two instruments is accounted for by using scene-specific SCIAMACHY hyper-spectral measurements[4, 5].

2. METHODOLOGY

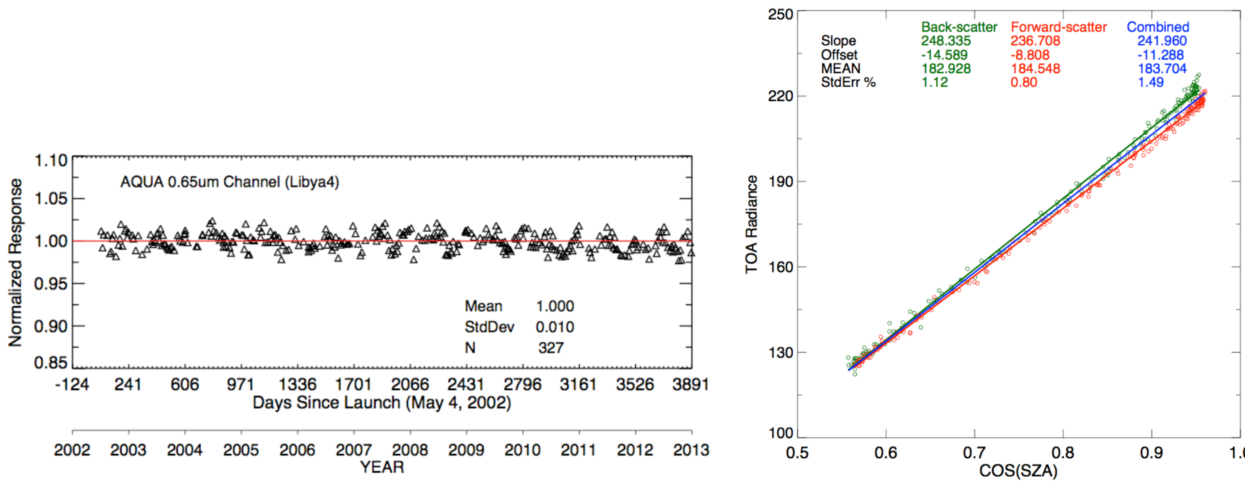
2.1 Dataset selection

The Aqua-MODIS Collection-6 Level-1b Band-1 (0.65 μm) 1-km pixle level sub-sampled at every other pixel and scan line are used in this study. Aqua-MODIS is chosen because it is better characterized and more stable[6] (within 1% per decade) compared to Terra-MODIS. For VIIRS, the NPP VIIRS Land PEATE AS3100 product is used, which has an updated visible calibration (Summer 2013) from the VIIRS calibration team, which has removed all known instrument anomalies. This product was especially reformatted for the CERES project to provide a pixel-level resolution and file format similar to the MODIS level 1B HDF files. The Aqua-MODIS and VIIRS data are both obtained from the NASA Langley Atmospheric Data Center (ASDC). The SCIAMACHY Level-1B data (SCI_NL_1P, Version 7.03), produced with the European Space Agency (ESA)-distributed data calibrator, was used to extract the SCIAMACHY TOA hyperspectral radiances.

2.2 Invariant desert-based calibration approach

Stable desert targets are extensively used to assess the post-launch radiometric calibration of satellite sensors. Numerous studies[7, 8, 9] have identified the Libya-4 desert as one of the most invariant desert calibration targets on Earth. It has been used to monitor the long-term stability of many optical sensors including Landsat Multispectral Scanner (MSS)[10], Thematic Mapper (TM)[11], and Enhanced Thematic Mapper plus (ETM+)[12, 13], AVHRR[14], Aqua and Terra MODIS[6, 12, 13], and the Meteosat imagers[15]. Successful attempts have also been made to use Libya-4 as a reference to determine the absolute calibration coefficients of satellite sensors[5, 16]. Using five years of clear-sky calibrated radiance measurements taken from the Meteosat-9 imager (0.65 μm) on a daily basis, Bhatt et al.[5] showed that the ground site and the atmospheric column above Libya-4 form an invariant system together. This suggests a possibility of deriving a radiance calibration model using only the clear-sky observations from the top-of-atmosphere. In this study, ten years of clear-sky measurements from the Aqua-MODIS Band 1 is used to characterize Libya-4 and to obtain a TOA radiance model for a near-nadir condition (viewing zenith angle < 10°). The region-of-interest used in this study is a 0.5° X 0.5° region centered at 28.6° latitude and 23.4° west longitude. Figure 1(a) shows the life-time response of the Aqua-MODIS Band 1 over Libya-4 computed from nadir TOA reflectance measurements that are normalized by a site-specific semi-empirical BRDF model based on two kernel functions as described by Roujean et al.[17]. The clear-sky days are identified based on a spatial homogeneity test performed on the pixel-level radaînces within the ROI[3, 5]. The lowest standard deviation of pixel-level radiances are found on clear-sky days and the standard deviation was found to be very consistent through out the year. Based on the visible inspection of the standard deviation profile on clear-sky days, a threshold was determined to identify and eliminate the cloudy and dust storm observations. The temporal standard deviation of the normalized data shows that the Libya-4 site is stable within 1% over the last decade.

The near-nadir observed TOA radiances over Libya-4 used in Figure 1(a) are plotted as a function of solar zenith and scattering direction in Figure 1(b). The plot clearly shows that the observed TOA radiances are slightly darker in the forward scattering (RAZ > 90) and brighter in the backward scattering (RAZ < 90) direction. It is presumed that the presence and orientation of large sand dunes over Libya-4 is the cause of this feature. Therefore, the forward and backward scattering observations are separately regressed linearly. The standard error derived from the forward scatter radiances is almost half of the standard error based on the combined forward and backscatter radiances. Both the forward and backscatter Aqua-MODIS TOA radiance linear regressions are then used to predict the near-nadir TOA radiance for the VIIRS M5 channel for a given solar zenith angle. The predicted radiance is adjusted for the spectral correction between the VIIRS M5 and MODIS Band 1 channels using the SCIAMACHY hyperspectral measurements over Libya-4, which is described later in section 2.4. The MODIS predicted radiance is then compared with the actual measured TOA radiance of VIIRS to assess the calibration of the M5 channel.



(a) (b)

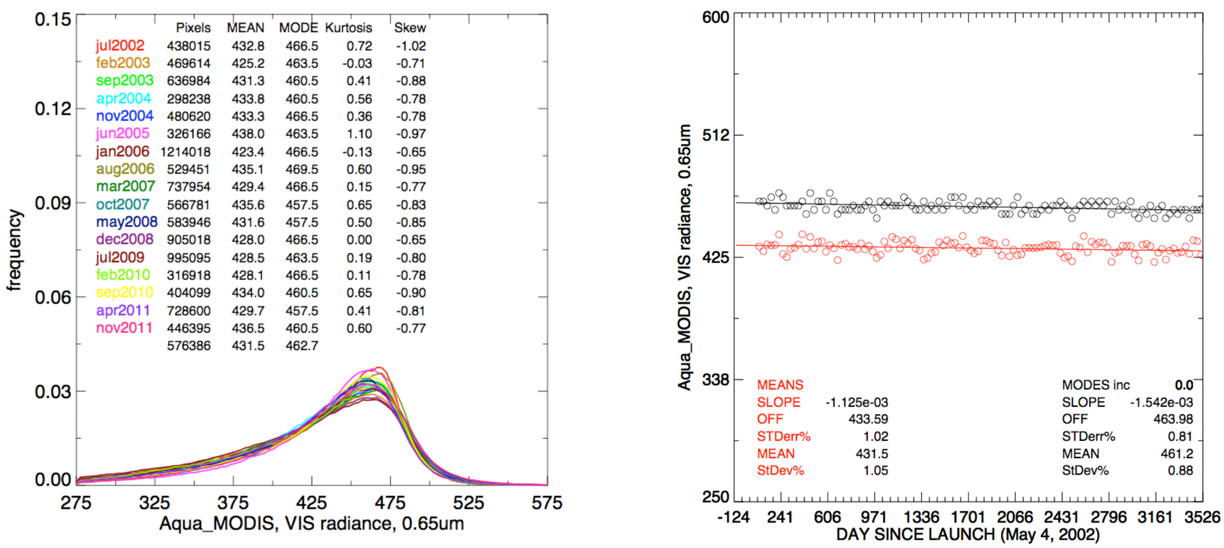
Figure 1. (a) Temporal stability of Libya-4 derived from 10-years of Aqua-MODIS Band 1 (0.65 µm) TOA radiances normalized by a kernel-driven BRDF model, (b) The same Libya-4 near-nadir TOA Aqua-MODIS Band 1 radiances stratified by scattering angle as function of the cosine solar zenith angle

2.3 DCC calibration approach

DCCs are the brightest terrestrial invariant targets located over the tropics. They have the highest signal-to-noise ratio and nearly flat reflectance spectra in the visible spectrum. Because they are located at the tropopause, the impact of water vapor absorption and aerosols in TOA reflectance measurements is minimal. They can be identified using a simple IR threshold because they are the coldest targets at the tropics. DCCs are thus an ideal visible calibration target viewed by all satellites.

Hu et al.[18] made the first attempt of using the collective DCC pixel-level radiances on a monthly basis to examine the calibration stability of the CERES shortwave measurements on board the Tropical Rainfall Measuring Mission (TRMM), as well as of the Visible and Infrared Scanner (VIRS) and MODIS imagers on TRMM and Terra satellites, respectively. Later, Doelling et al.[19] refined the technique to monitor the calibration drift of the Advanced Very High Resolution Radiometer (AVHRR) sensors on board the NOAA-16 and NOAA-17 satellites. A simple IR threshold of 205K was used to identify the DCC pixels. Doelling et al.[20] also characterized DCC narrowband albedo response by analyzing SZA, VZA, AZA, Band 31 (11 µm) brightness temperature (BT 11µm), and geo-location effects on Aqua-MODIS DCC response. It was found that the DCC response could be affected by both BT 11µm and geo-location.

This study follows the approach of the GSICS DCC ATBD[21] with only slight modifications. In order to minimize the effect of regional variability in the DCC response, a fixed DCC domain extending from 120°E to 160°E longitude, and 20°N to 20°S latitude is defined over the Tropical Western Pacific (TWP), which has the highest frequency of DCC events. DCC radiance pixels are identified within the domain using an IR threshold of 205°K. The so identified pixels are further passed through spatial uniformity tests and other selection criteria to get rid of optically thin clouds. In general, a DCC radiance pixel is considered valid provided it met the following criteria: BT11µm < 205.0° K, SZA < 40°, VZA < 40°, 10° < AZA < 170°, σ(BT11µm) < 1.0° K, and σ(VIS) <3%. The anisotropic correction of each DCC pixel is performed using the angular distribution model (ADM) by Hu et al[18], which normalizes all DCC response to a common set of angular conditions. The normalized DCC radiances were then compiled into monthly probability distribution functions (PDFs). The statistical mode and mean is computed for each monthly PDF, and are tracked throughout time to monitor the expected DCC response. Figure 2(a) shows the monthly PDFs of the anisotropically corrected DCC radiances from Aqua-MODIS Band 1 are very consistent as expected from a well-calibrated instrument. The temporal invariance of the DCC target is shown in Figure 2(b) by plotting the monthly PDF mean and mode DCC radiances as a function of time. The temporal standard deviation of monthly PDF mode shows the variability of only 0.88% in the DCC response over 9 years and similar to the 1.0% obtained over Libya-4. A mean (461.2 $Wm^{-2}sr^{-1}\mu m^{-1}$) of all the monthly PDF modes is computed as the expected DCC response over the TWP DCC domain.



(a) (b)

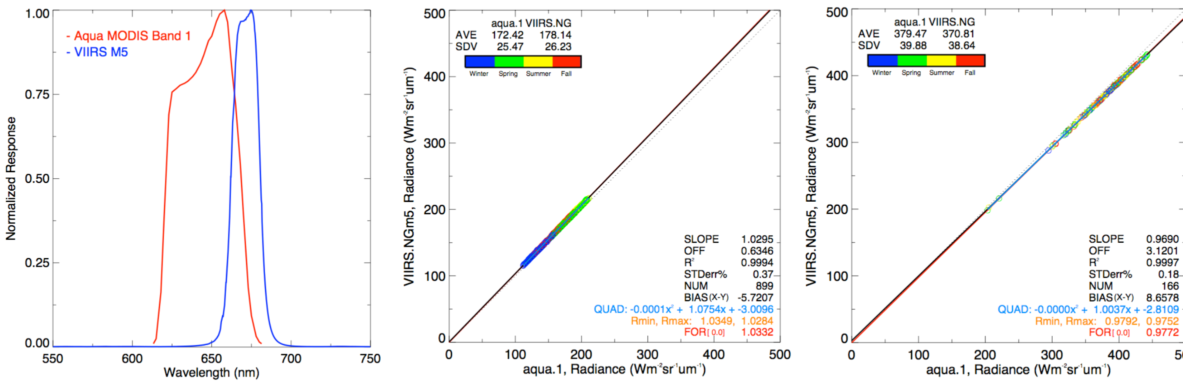
Figure 2. (a) The Aqua-MODIS DCC monthly PDFs over the TWP domain. (b) Aqua-MODIS DCC monthly PDF mode and mean radiance trends between 2002 and 2012 showing the invariance of the DCC target.

Since NPP-VIIRS and Aqua-MODIS are both in 1:30 PM sun-synchronous orbits, both sensors should observe the same DCC over the TWP. To transfer the Aqua-MODIS calibration to VIIRS the identical MODIS procedure is applied to the VIIRS M5 channel DCC pixel radiances to compute the monthly PDFs over the same domain. The VIIRS DCC monthly PDF mode radiances are then compared to the 9-year mean MODIS DCC mode radiance. The mean MODIS DCC mode radiance is first adjusted for the spectral correction between the VIIRS M5 and MODIS Band 1 channels using the SCIAMACHY hyperspectral measurements over DCC, which is described later in section 2.4.

2.4 Spectral band corrections

Assessment of the VIIRS calibration using the desert and DCC models obtained from Aqua-MODIS is incomplete without spectral band corrections. Figure 3(a) shows that the MODIS Band 1 SRF is much wider than that of VIIRS M5 channel. For this study, the high spectral resolution reflected solar radiances measured by SCIAMACHY over the Libya-4 and the DCC targets are used to derive the spectral band adjustment factor (SBAF) needed to account for the spectral differences between the VIIRS M5 and Aqua-MODIS Band 1 channels. This method follows the technique described by Doelling et al.[4], where the target-specific reflected spectra from each SCIAMACHY pixel is convolved with VIIRS and MODIS SRFs to estimate pseudo-imager radiances. The VIIRS pseudo-radiances are then regressed against the MODIS pseudo-radiances, and the forced slope (regression through zero) is used as the SBAF. The SBAF should be applied to the Aqua-MODIS radiances to arrive at a spectrally corrected predicted VIIRS radiance.

SCIAMACHY has a footprint size of 30 km by 240 km and a spectral resolution between 0.2 and 0.5nm over a wavelength range of 240 to 1700 nm. Bhatt et al[5]. performed a sensitivity analysis to determine the impact of the SCIAMACHY pixel spatial mismatch over Libya-4 on the computation of SBAF and was found to be insignificant. This study uses the same approach of selecting SCIAMACHY pixels over Libya-4 as described by Bhatt et al[5]. Similarly, the cloud conditions of the SCIAMACHY footprints for obtaining the DCC reflectance spectra are determined using nearly coincident Terra-MODIS cloud retrievals from the CERES Single Scanner Footprint level-2 product as described by Doelling et al.[22]. A footprint is considered as DCC if the cloud-top-temperature is less than 205°k and the optical depth is greater than 70 at the center footprint location. The regressions of the VIIRS M5 and MODIS Band 1 pseudo-radiances computed from the SCIAMACHY pixels over Libya-4 and DCC are shown in Figure 3 (b) and (c), respectively. The SBAF over Libya-4 shows that the TOA radiance measured by VIIRS over Libya-4 is 3.3% higher than that of MODIS due to the spectral differences between the two channels. On the other hand, the DCC response from the MODIS channel is expected to be brighter than the VIIRS channel by 2.3%, as indicated by the DCC SBAF. If a flat spectral response is assumed, which is computed from the MCST solar irradiance spectra and convolved with the band SRF, then VIIRS is darker than MODIS by 4.6%. Since DCC are white reflectors in the visible, the difference between the DCC and spectrally flat radiance signal, between MODIS and VIIRS is due to the gaseous absorptive bands, such as ozone, that are not shared by the two bands.



(a) (b) (c)

Figure 3. (a) SRFs of Aqua-MODIS Band 1 and VIIRS M5 channels. Regression of SCIAMACHY-based pseudo-radiances for the VIIRS M5 and MODIS Band 1 channels over Libya-4 (b) and DCC (c).

3. RESULTS

The desert and DCC radiance models obtained from near-nadir Aqua-MODIS Band 1 measurements are used to compute the corresponding expected radiance for the VIIRS M5 channel under similar angular and spatial conditions. The predicted TOA radiance values from the MODIS models are then adjusted for spectral corrections using the appropriate SBAF. The ratio of actual VIIRS measurements and their corresponding expected values computed from the MODIS-based models are plotted as a function of time for both the desert and DCC targets to examine the stability of and any possible bias between the VIIRS M5 channel and MODIS Band 1 calibration. Figure 4 shows the ratio is stable over time and is close to 1, as expected from two equally well-calibrated instruments. The mean ratio difference between deserts and DCC is 0.2%, verifying the robustness of both independent calibration approaches. The DCC approach has a smaller standard error about the linear trend and is better suited to assess the VIIRS stability. The results indicate that the VIIRS calibration team has removed most of the instrument calibration drifts in the re-calibrated VIIRS Land PEATE AS3100 product.

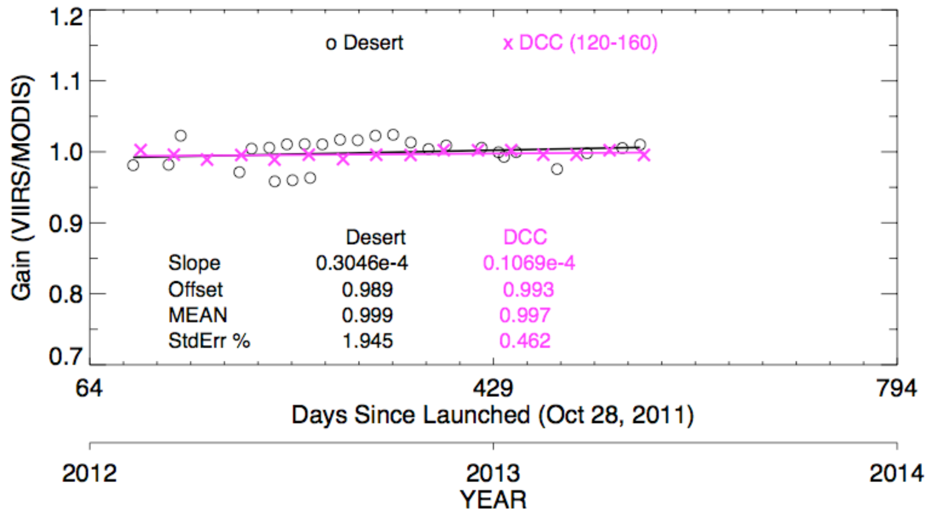


Figure 4. Comparison of the VIIRS and MODIS TOA radiance ratios over Libya-4 (black circle) and the DCC (magenta x) invariant targets.

4. CONCLUSIONS

An initial assessment of the VIIRS M5 channel calibration is performed using the Libya-4 desert and the DCCs as invariant targets. In this study Aqua-MODIS Band 1 is used as the calibration reference. The nine years of near-nadir measurements taken from Aqua-MODIS over Libya-4 are used to construct a TOA radiance model of the desert. Two separate linear models are used for forward and backward scattering based on the relative azimuth angle. The models are used to predict TOA radiances for the VIIRS M5 channel under similar viewing and solar angular conditions. Similarly, the DCC measurements from Aqua-MODIS over the TWP region are used to compute an expected DCC radiance value over the region. The DCC radiance pixels are identified using an IR threshold of 205K and spatial homogeneity tests in the visible and IR channels. The DCC radiances are corrected for anisotropy using the Hu model. The normalized DCC response computed from Aqua-MODIS is then used as a expected reference DCC radiance for inter-comparison with VIIRS. The SRF difference between VIIRS M5 and Aqua-MODIS Band 1 was corrected using pseudo SCIAMACHY footprint radiances observed over each of the calibration targets. The assessment shows an excellent agreement (0.1% for Libya-4 and 0.3% for DCC) in the measured TOA radiances from both the instruments. This concludes the VIIRS M5 channel calibration quality is comparable to that of Aqua-MODIS and thus it can serve as a reference for calibrating GEOs in future for the CERES project.

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